Office of Naval Research Project

The Predictability of Extratropical Transition and of its Impact on the Downstream Flow

Award Number: N00014-06-1-0432

Final Report

Sarah C. Jones, Doris Anwender, Michael Riemer
Institut für Meteorologie und Klimaforschung
Universität Karlsruhe
Kaiserstr. 12
76128 Karlsruhe

March 28, 2008

Contents

1 Objectives

The goal of this project was to investigate the basic mechanisms that determine the predictability of tropical cyclones undergoing extratropical transition (ET) and of their subsequent impact on the downstream midlatitude flow.

The specific objectives were

- to analyze the representation of historical ET events in the North Atlantic and the western North Pacific in the European Centre of Medium Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) using a combination of principal component and cluster analysis.

- to investigate the sensitivity of EPS forecasts to initial ensemble perturbations associated with the typhoon undergoing ET, to the stochastic physics and to higher horizontal resolution.

- to investigate the impact of dropsonde data in tropical cyclones on the forecast of the downstream flow.

- to investigate the mechanisms by which the tropical cyclone modifies the downstream flow using idealised modeling and potential vorticity (PV) inversion.

- to assess the variability in the structure of the low-level wind field during ET using results from idealised model calculations.

2 Scientific Importance

Tropical cyclones that are undergoing extratropical transition (ET) are characterized by an increased forward speed, increased asymmetry in the wind and precipitation fields and an increase in horizontal scale. Thus, although the maximum wind speed typically decreases, they still pose a considerable threat to maritime activities as the increased forward speed can lead to a dramatic and rapid increase in wave height and the increase in scale leads to a larger areal coverage of gale force winds. Furthermore, the interaction of the tropical cyclone with the midlatitude flow can result in the excitation of a Rossby wave packet that can initiate explosive development downstream of the ET system itself. Predicting ET poses a considerable challenge for numerical weather forecast systems as the interaction between the tropical cyclone and the midlatitude flow covers a large range of scales from the convective inner-core of a tropical cyclone to the synoptic-to-planetary-scale Rossby waves. Reduced predictability may be associated with the direct impact of an ET event, if the ex-tropical cyclone is predicted to reach a continent as an extratropical storm. Arguably the larger impact on predictability, however, occurs due to the above mentioned Rossby wave train. This may initiate extratropical cyclogenesis in the eastern ocean basin, or modify existent flow patterns enhancing the risk of severe precipitation events. Due to its influence on the downstream flow an ET event can lead to significantly reduced predictability over an entire ocean basin.

3 Extratropical Transition in Ensemble Prediction

3.1 Case studies

Since there are often large errors in deterministic forecasts of ET (Jones et al., 2003), it is essential to obtain information about the probability of a particular forecast. Ensemble forecasts not only give information about the predictability of synoptic events but represent also a large set of dynamically consistent possible evolutions of the events. Furthermore, they can give information about scenarios that are less likely but still possible.

Five ET cases including strong and weak events both in the western North Pacific and the North Atlantic were investigated with the ECMWF EPS. All five cases exhibited a characteristic trough-ridge-trough pattern in the midlatitudes on the dynamic tropopause, consisting of the trough that interacts with the respective TC, a ridge directly downstream and a second trough downstream of the ridge. It became evident that the ET events were associated with high uncertainty in the EPS.

The standard deviation was used to quantify the uncertainty at 200 and 500 hPa. The regions of highest standard deviation in the major TC cases could be found from 18 to 60 h after ET in a trough upstream of the ET, directly associated with the ET, and in a downstream trough. As the strong increase of standard deviation was always seen shortly after completion of the ET irrespective of the forecast interval prior to it, evidence is given that the uncertainty is tied to the ET. For example, for Typhoon Maemi (2003, Fig. 1) the region of increased standard deviation originating near 130E is due to different representations of the ET of Maemi. The mid-Pacific high standard deviation is associated with the variability of a downstream trough.

In the weak ET cases the highest uncertainties could be found somewhat later after ET than for the strong cases, at the location where the remnants of the weak ET systems merged with the respective midlatitude system. While the overall uncertainty in the ensemble grows for longer forecast times, several days after ET the high values of standard deviation associated with the ET event decrease to more normal values compared with regions that are not influenced by the ET. This decrease further demonstrates the connection between the high variability in the ensemble and the ET event.

Initializing the forecast at times, when the relative location of the respective upstream trough to the recurving TC, referred to here as "phasing", was better defined, yielded much lower uncertainty for the same forecast lead time (Fig. 1 b). The connection of the increased variability among ensemble members to the respective ET is reduced but still a comparatively high uncertainty associated with the ET event remains.

In order to investigate the variability of the ensemble members in association with extratropical transition we analysed the five cases of ET in the two ocean basins using principal component (PC) analysis and clustering techniques (Harr et al., 2007). The leading empirical orthogonal functions (EOFs) are calculated for the region of interest. They identify the locations where the variability of the ensemble members is largest i.e. the centers of action. The leading EOF identifies the dominant synoptic pattern that contributes most to the forecast variability.

It was found that the EOFs in all five investigated cases showed robust structures associated with the ETs. The variability in the EPS revealed by

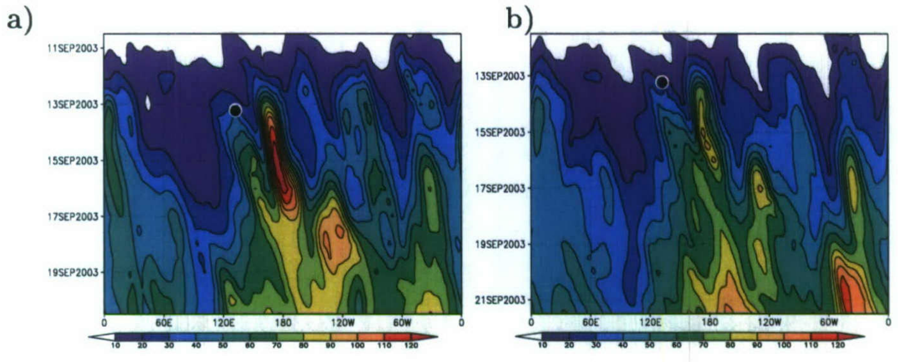
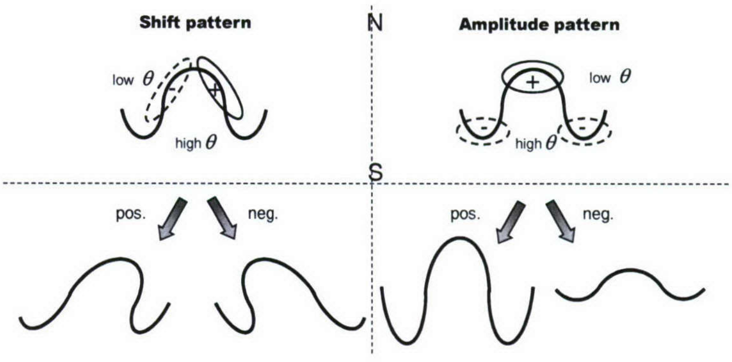


Figure 1: Standard deviation of 51 ECMWF ensemble members for 500hPa height during the ET of Typhoon Maemi (black dot). Forecast from a) 10 and b) 11 September 2003 1200 UTC.

them is related to physical scenarios. The uncertainty was based mainly on two variability patterns: one pattern, that describes an east-west shift of the trough-ridge-trough pattern (Fig. 2a), and another one that describes the amplitude of the trough-ridge-trough pattern (Fig. 2b). Although the maxima of variability associated with ET decreased with decreasing forecast time, the variability patterns remained connected to the synoptic features of the ET.

By the aid of a c-means fuzzy cluster analysis applied to the first two principal components ensemble forecasts were grouped into different clusters according to similar forecast scenarios associated with the ETs. It could be seen that similar signs of contribution of the individual clusters to the variability patterns in all five cases led to similar developments of the ETs. An eastward shift of the trough-ridge-trough pattern implies a faster motion and development of the ET system, whereas a westward shift implies a slower motion and development than in the other clusters (Fig. 2c). A higher amplitude of the trough-ridge-trough pattern in one cluster would imply a deeper re-intensification of the system and a lower amplitude would imply a weaker

a) b)



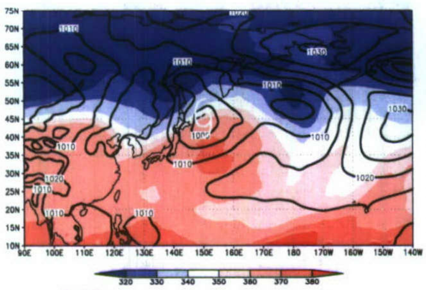
c) d)

Figure 2: Schematic of the first two EOFs (thin black lines with + and - signs, top) denoting a) the shift and b) the amplitude pattern. The dynamic tropopause is represented schematically. The thick black line represents the strong potential temperature gradient in the midlatitudes. South of it the potential temperature values should be high, north of it they should be low. Synoptic patterns that result from the contribution to c) the shift and d) the amplitude pattern.

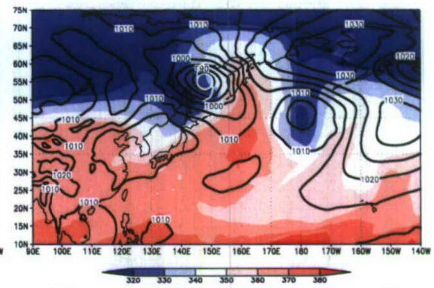
re-intensification than in the other clusters (Fig. 2d). These links have the potential to give the forecaster an indication of the future development of the system from examining the pattern of the dynamic tropopause during ET. For example, in the case of Maemi the shift and amplitude patterns are optimally separated in the EOFs. Thus, the clusters show the effect of the contribution to the variability patterns best (Fig. 3).

With the aid of the analysis method a range of very different possible atmospheric developments in the regions of high variability were extracted. Through the clustering, probabilities could be assigned to each of these de-

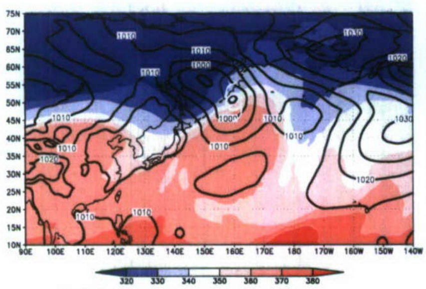
a) **shift 0** **amp -**



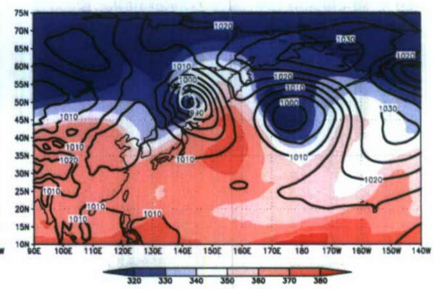
b) **shift 0** **amp +**



c) **shift +** **amp 0**



d) **shift -** **amp 0**



e) **shift 0** **amp 0**

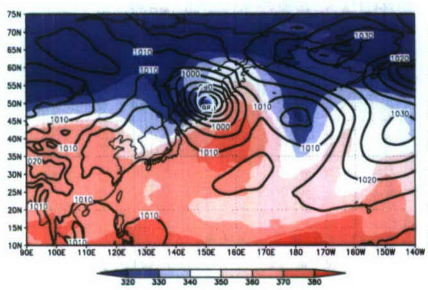


Figure 3: 5 clusters for Maemi for the ensemble forecast from 1200 UTC 10 September 2003 valid on 0000 UTC 15 September, i. e. 12 h after the investigation time. Potential temperature at the dynamic tropopause (shaded, K), surface pressure (contours, interval: 5 hPa).

velopments based on the number of members contained in each cluster. Furthermore, indications of atmospheric evolutions associated with the ETs that are not probable but possible are given. Hence, the large number of ensemble members, showing very different developments during ET, is reduced to a small number of ET scenarios that are provided with a probability of the ET event occurring. Thus, the information contained in the EPS can be made accessible to a forecaster.

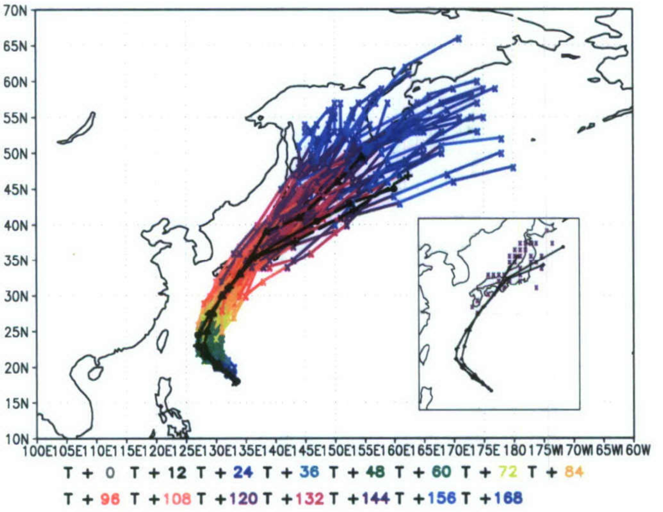
3.2 Experiments

In the ECMWF EPS initial perturbations for the ensemble members are obtained by calculating singular vectors (SV) with linearized diabatic physics for areas targeted around tropical cyclones. This procedure aims to capture the high uncertainty associated with a decaying tropical cyclone moving into the extratropics.

We carried out experiments rerunning the EPS for the specific ET case of Typhoon Tokage (2004). The aim was to compare the influence of targeted perturbations, stochastic physics and higher resolution on the track and intensity forecasts, the representation of overall spread during an ET, the downstream propagation of uncertainties introduced by an ET event and the grouping of the ensemble members in the regions of uncertainties.

The EPS experiments showed that sufficient ensemble spread in the track and improved spread in the intensity forecast depends strongly on the additional perturbations targeted on Tokage. Without these, the track spread in the forecasts, especially that around the recurvature and ET of Tokage, was underestimated and the analysis was not contained within the ensemble members (Fig. 4).

In general, the targeted SVs are expected to be appropriate to perturb larger scale features associated with the track forecast. The stochastic physics are needed to perturb small scale processes, such as convection in the inner core of the TC, that determine the intensity (Puri et al., 2001). In our case, however, the stochastic physics mainly yields sufficient spread in the intensity for the forecast times before ET. At ET time and thereafter, the targeted perturbations were responsible for weakening while the stochastic physics led to more deepening than seen in runs with neither targeted perturbations nor a)



b)

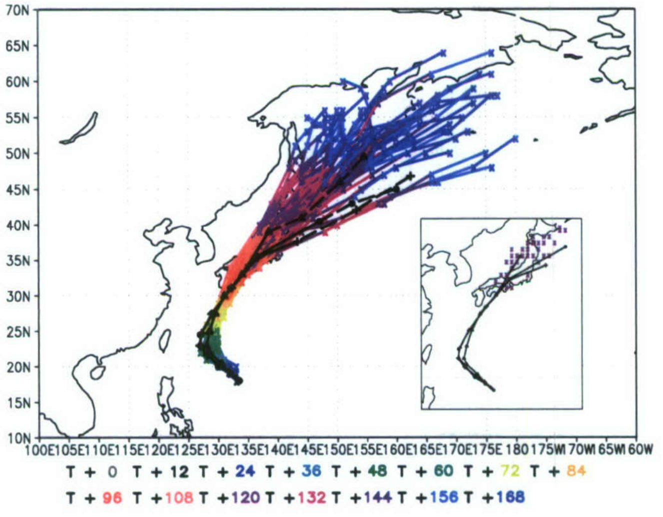


Figure 4: Tracks for Tokage based on location of minimum sea level pressure for the runs with (a) and without (b) targeted perturbations on the TC. ECMWF analysis (black line with circles), best track (black line with crosses), deterministic forecast (black line with triangles) and ensemble forecast (colors) from FCST1 for 7 days. Analysis dashed after ET. Right lower corner: Positions of the ensemble members at ET time (purple x), analysis, best track and deterministic forecast only shown until ET time.

stochastic physics.

Tokage weakened considerably shortly after its landfall on Japan. The extent and rapidity of the weakening was not contained in the ensemble forecasts with targeted perturbations or with stochastic physics. Clearly, the weakening, which was probably associated with the landfall in Japan, is too severe a challenge for parameterization schemes. Other case studies of the representation of the intensity in the ensemble during the landfall of a typhoon on Japan or other small islands might yield insightful comparisons.

The new high resolution model cycle with targeted perturbations shows the best spread in track and intensity forecast. More members show a quick movement of Tokage. This is, however, due to other innovations rather than to the higher horizontal resolution which is shown by tests runs with the new model cycle with the lower horizontal resolution used in the old model cycle. Even with the new model cycle with high resolution and with the targeted perturbations on Tokage the ensemble forecast of the intensity does not encompass the analysis over the 24h period of weakening.

The impact of the SVs targeted on Tokage propagates downstream with the group velocity of a Rossby-wave-train that has been excited by the interaction of Tokage with the midlatitudes (Fig. 5a, c, e, g). The amplitude of the wave packet determines the transport of wave energy which can trigger cyclogenesis far away from the ET event. At 20° per day the group velocity is slightly smaller than that found by Szunyogh et al. (2002). The growth and downstream propagation of the impact of the targeted SVs on Tokage yields a good measure of the rapidity and the extent of the downstream propagation of errors growing in association with ET. The results indicate that an ET event can reduce the predictability over an entire ocean basin.

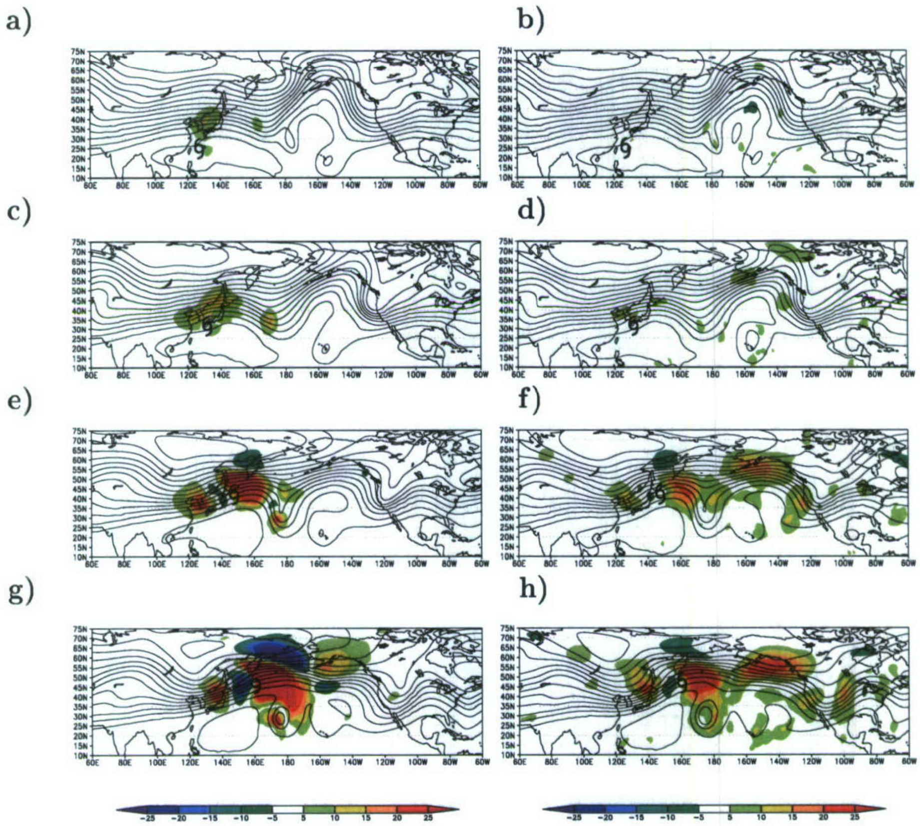


Figure 5: RMSD difference of the geopotential height (m) at 200 hPa between the ensemble forecasts from 1200 UTC 16 October 2004 with and without targeted perturbations on Tokage (a, c, e, g) and with and without stochastic physics (b, d, f, h) (shaded). Forecasts for 48 hours prior to ET (a,b), for 24 hours (c,d) prior to ET, for ET (e,f) and for 24 hours after ET (g,h). ECMWF control forecast of geopotential height (black contours). Eady index (blue contours, values ≥ 0.6, interval: 0.4).

The strong growth of the effect due to the stochastic physics in the vicinity of the ET and the partial downstream propagation of this effect demonstrates that there is a distinct reduction of predictability due to parametrized processes associated with the ET (Fig. 5b, d, f, h). Stochastic physics can have an influence on the downstream predictability through perturbations caused by Tokage's outflow impinging on the midlatitude jet. The uncertainties due

a) b)

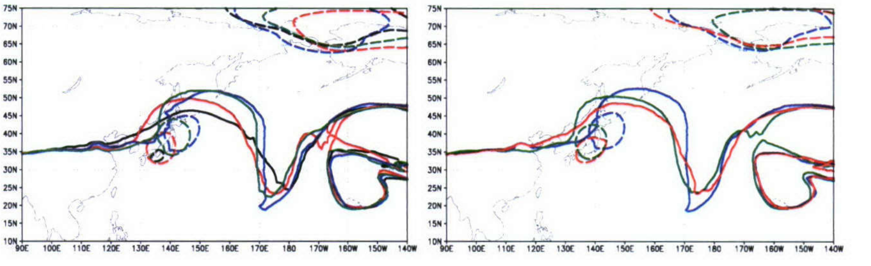


Figure 6: Spaghetti plots of the cluster means of the 350 K isentrope and the 995 hPa mean sea level pressure isobar. Ensemble forecast for Tokage a) with and b) without perturbations targeted on Tokage from 1200 UTC 16 October 2004 valid on 1200 UTC 21 October 2004.

to parametrized processes continue growing beyond the medium range.

The use of the EOF/cluster analysis showed that 4 clusters were obtained only in the runs with targeted perturbations. With stochastic physics alone or with high resolution alone, 3 clusters were found. Only the targeted perturbations with the old model cycle yield one cluster that shows no ET and, hence, is weaker than the analysis. The reason for the decay of Tokage in this cluster, however, was not the landfall as in the analysis, but that the TC was too far south of the midlatitude baroclinic zone. Even with the higher resolution and with targeted perturbations on Tokage only one cluster showed the weakening due to the landfall. However, in this cluster the ex-TC re-intensified subsequently, as in all the other clusters. This is in contradiction to the analysis.

4 Influence of dropsonde data on downstream forecasts

The reduced predictability downstream of the tropical cyclone was demonstrated in the study using the ECMWF EPS. These results lead to the question as to whether enhanced observations in and around the tropical cyclone improve numerical forecasts downstream of an ET event. The National Hurricane Center and Hurricane Research Division (HRD) have been conducting reconnaissance flights around tropical cyclones for a number of years. Measurements from dropsondes released from aircraft are assimilated at operational forecast centers. Targeted observations aimed at improving hurricane track forecasts were made in areas of increased ensemble spread of the deep layer mean wind. For short-range forecasts the additional hurricane data leads to a track forecast error reduction (Aberson, 2003). In this study we investigate the impact of observations in the vicinity of tropical cyclones on the forecasts of the downstream flow.

We compare two sets of forecasts from the National Centers for Environmental Prediction global model. The first is the operational forecast in which dropsonde data is assimilated routinely, although no humidity data is included. This forecast is referred to here as ALLDROP. The second set contains forecasts rerun by Sim Aberson of NOAA/HRD from an analysis cycle in which no dropsonde data is included for the whole hurricane season, referred to here as NODROP. A total of ten forecasts from the 2003, 2004 and 2005 hurricane seasons were investigated here (Boettcher, 2006).

In Fig. 7 the differences between ALLDROP and NODROP for a forecast of Hurricane Ivan (2004) are shown. In the lower and mid troposphere

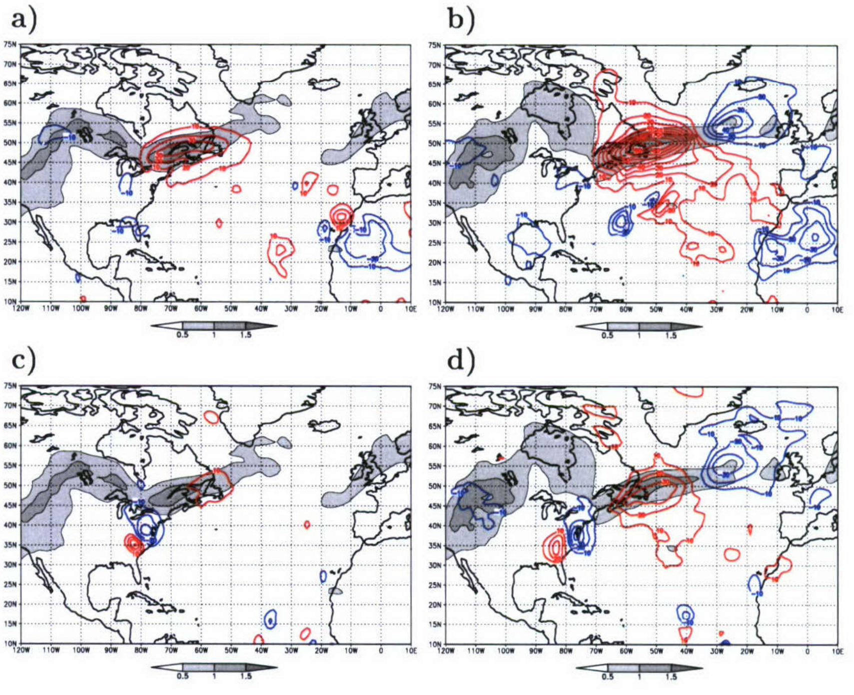


Figure 7: Forecast for Hurricane Ivan from 1200 UTC 16 September 2004. Difference ALLDROP-NODROP (contours), Eady index > 0.5 (day^{-1}, shaded) at a,b) 200 hPa and c,d) 500 hPa for a,c) +60 h and b,d) +48 h.

differences between the forecasts arise due to different locations and intensities of the tropical storm in ALLDROP and NODROP. At upper-levels the differences develop in the region of the midlatitude jetstream. These differences propagate downstream and grow in regions of baroclinic instability, as illustrated by the Eady index. A detailed examination of the forecasts suggests that the differences at upper-levels arise due to the interaction of the tropical cyclone outflow with the sloping midlatitude tropopause. A similar sensitivity is found for forecasts of Hurricanes Bonnie and Charley 2004 (not shown).

The impact of dropsonde observations in the vicinity of hurricanes on the

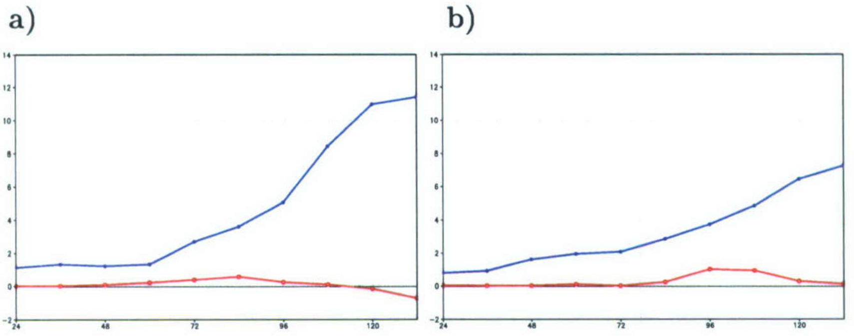


Figure 8: Forecast error reduction (red), forecast error of ALLDROP (blue) for the forecast for Ivan from 1200 UTC 16 September 2004 for a) the Atlantic and b) Europe.

downstream flow is quantified using the mean forecast error reduction Fn (Szunyogh et al., 2000) given by

$$F_n = \frac{1}{n}\Sigma(|f_{NODROP} - f_{analysis}| - |f_{ALLDROP} - f_{analysis}|) \quad (1)$$

where the summation is calculated over n gridpoints in the region"Atlantic" (60-20°W;35-60°N) or "Europe" (20°W-20°E;35-70°N). For Hurricane Ivan we see a moderate forecast error reduction over the Atlantic after 72 h and then an increased error after 120 h (Fig. 8). The forecast improvement is seen further downstream, giving a forecast error reduction of up to 27% over Europe after 96 h. For ten cases from 2003-2005 (Fig. 9) there is little change in the forecast for the Atlantic due to the inclusion of dropsonde data. For Europe a forecast error reduction is seen after 84 h with the maximum reduction of 15% after 108 h forecast.

This study indicates that observations in the vicinity of a tropical cyclone that subsequently undergoes ET can have a positive impact on the forecast of the downstream flow. However, the dropsonde data investigated here has certain limitations. First, the observations investigated here were not designed to improve the downstream forecast. Second, no observations were available

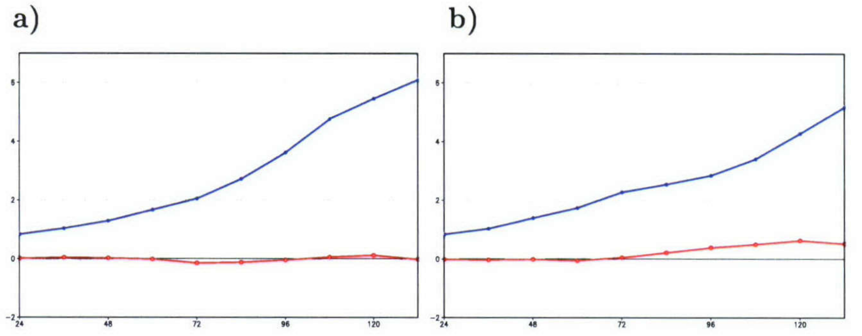


Figure 9: As Fig. 8 for 10 forecasts in 2003, 2004 and 2005.

that documented the interaction of an extratropical transition system with the mid-latitude tropopause. Finally, dropsonde humidity data is not used in forecasts.

5 Idealized modelling studies of Extratropical Transition

In order to investigate the mechanisms leading to the reduced predictability described in the previous section we conducted a numerical modeling study to investigate the impact of a tropical cyclone undergoing extratropical transition on the midlatitude synoptic-scale flow. Three idealised midlatitude flow scenarios were investigated: a straight jet stream, developing baroclinic systems excited by a localized initial perturbation and a mature baroclinic wave. The numerical experiments were performed using the fifth generation NCAR / Penn State mesoscale model (MM5) in which we implemented periodic boundary conditions. We used a channel configuration with the full latitudinal variability of the Coriolis parameter. The channel was approximately 18 000 km in the east-west direction and 11 000 km in the north-south direction with 60 km horizontal resolution. A tropical cyclone was inserted south of the midlatitude flow. An automatically moving nest with 20 km resolution covered the immediate vicinity of the transforming tropical cyclone. The sea surface temperature was a time invariant function of latitude. Hovmoeller diagrams were used to investigate the magnitude and the downstream propagation of the impact of ET. Piecewise inversion of potential vorticity, complemented by the partitioning of the flow into its rotational and divergent parts, was applied in the straight jet case to assess the impact of the ET system on the midlatitude flow quantitatively.

5.1 Straight jet case

In our basic experiment a tropical cyclone interacts with the most simplified representation of the midlatitude flow regime: a straight jet. The prominent features of the interaction are a jet streak that forms in the region where the outflow of the tropical cyclone impinges on the jet and a ridge-trough couplet on the tropopause. Both features amplify during the interaction (Fig. 10a, b). Beneath the left exit region of the jet streak rapid surface cyclogenesis takes place (Fig. 10b, c). At upper levels the ridge-trough pattern extends downstream as a wave pattern and initiates a family of cyclones (Fig. 10c, d)). The evolution downstream of ET can be viewed as downstream baroclinic development with the tropical cyclone undergoing ET acting as the initial perturbation. The temporal evolution of the upper-level wave pattern can be interpreted as the excitation of a Rossby wave train by the ET event and its subsequent propagation downstream (Fig. 11). We find also an indication of significant moisture transport into the midlatitudes associated with the ET system, both around its centre and ahead of the pronounced cold front (not

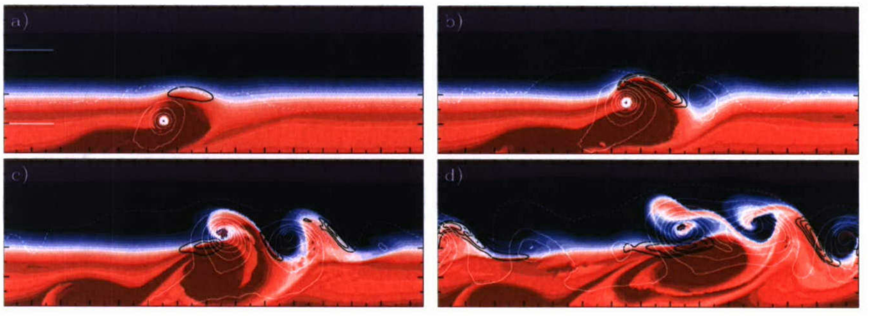


Figure 10: Section of the model domain that corresponds to 14° - 65° N, potential temperature (shaded) and wind speed higher than 45 ms^{-1} (thick contour lines, every 5 ms^{-1}) on the dynamic tropopause (2 PVU) and surface pressure (black contours, 995 hPa = solid, dashed for values smaller 995 hPa, every 5 hPa) for (a) 120 h, (b) 156 h, (c) 192 h and (d) 240 h for the straight jet experiment. Tick marks every 600 km. The two lines on the left of (a) denote the zonal band used for the Hovmöller diagram (see below).

shown).

We performed piecewise PV inversion to quantify the contribution of the non-divergent, balanced circulation associated with specific flow features to the evolution of the upper-level wave pattern. A Helmholtz partitioning of

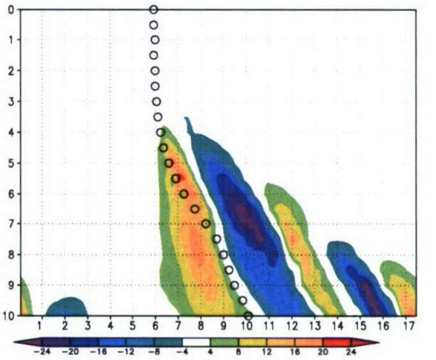


Figure 11: Hovmöller plot of the 200 hPa meridional wind speed (ms^{-1}) averaged over the zonal band of width 3000 km indicated in Fig. 10a for the straight jet experiment. Warm colors = southerlies, cold colors = northerlies. The x-axis is labeled in 103 km and the y-axis (time) in days. Open circle denote the meridional position of the ET system.

the flow was applied to account for the contribution of the divergent flow. Very early in the interaction the divergent flow within the outflow of the tropical cyclone is responsible for the building of the ridge (not shown). In the later stage of the interaction the balanced, cyclonic circulation of the decaying tropical cyclone is an important contributor to ridge amplification (Fig. 12a). The divergent component of the flow remains equally important but is no longer clearly attributable to the outflow alone (not shown). The balanced, non-divergent circulation associated with the outflow anomaly promotes phase-locking between the upper-level wave and the ET-system. Further, it contributes significantly to trough development downstream and to the formation of a low-Θ streamer extending into the south of the domain (Fig. 12b). Low-level feedback is negligible until late in the interaction and diabatic modification of the midlatitude PV gradient is not important for the building of the ridge directly downstream of ET either.

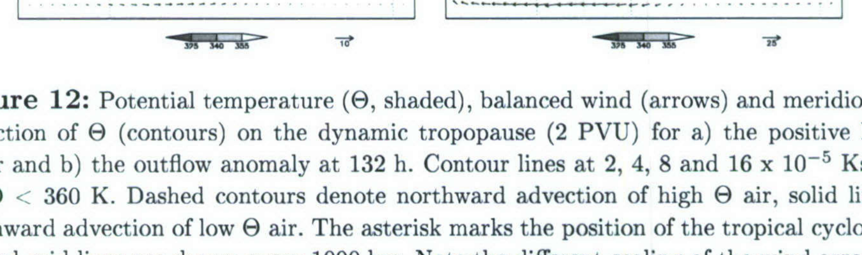


Figure 12: Potential temperature (Θ, shaded), balanced wind (arrows) and meridional advection of Θ (contours) on the dynamic tropopause (2 PVU) for a) the positive PV tower and b) the outflow anomaly at 132 h. Contour lines at 2, 4, 8 and 16 x 10^{-5} Ks^{-1} for $\Theta < 360$ K. Dashed contours denote northward advection of high Θ air, solid lines southward advection of low Θ air. The asterisk marks the position of the tropical cyclone. Dotted grid lines are drawn every 1000 km. Note the different scaling of the wind arrows. The arrow in the right panel denotes the axis of the ridge.

The PV diagnosis reveals that the circulation associated with the ET system has a profound impact on the evolution of the ridge-trough pattern over an extended period of time. This is in marked contrast to traditional initial value studies of baroclinic development in which the initial perturbation is embedded in the midlatitude flow, subject to strong horizontal and vertical shear, and thus loses its initial structure rapidly. In our experiments the tropical cyclone represents an external forcing on the jet in the early stage of the interaction. Although the tropical cyclone becomes embedded in the midlatitude flow during ET it still maintains a coherent structure for an extended period. Thus, the tropical cyclone can be compared to a long-lived local wave maker. Through this analogy it is clear that the structure of the ET system has a significant impact on the development downstream. This impact is here found to be greatest one wave length downstream of ET. In the tropical as well as in the transformation phase convective processes are essential for the maintenance of the coherent structure of the tropical cyclone. Thus a correct representation of the ET system, a challenge for current numerical weather prediction models, is of crucial importance not only for the forecast of ET itself but also for the predictability of the downstream flow.

Sensitivity experiments (not shown) highlight the importance of the atmospheric state in the midlatitudes for the propagation of the Rossby wave train. Consistent with the theory of Rossby wave propagation on a localized barotropic jet we find a higher group velocity for stronger jet streams. For a weaker jet the upper level disturbance has a more meridional orientation and a smaller wave length. This is consistent with the tropical cyclone acting on the jet as a localized wave maker. The low pressure system developing just downstream of ET also exhibits a greater tendency to the anticyclonic paradigm of life-cycle behavior for a weaker jet stream. Further, diabatic processes in the midlatitudes are found to be important for the amplitude of the upper-level wave train.

5.2 ET scenarios with baroclinic waves

A baroclinic wave constitutes a more realistic albeit more complex representation of the midlatitude flow. We consider two contrasting scenarios in greater detail: developing baroclinic systems excited by a localized initial perturbation (referred to as the developing case in the following) and a mature baroclinic wave excited by a periodic initial perturbation (mature case). In both scenarios the impact of the ET system on the baroclinic development is inferred from the differences between the baroclinic life cycle experiment (LC run) and an experiment in which the ET system is present within the integration domain (ET run).

Developing case

In the developing case the initial position of the tropical cyclone is chosen so that ET takes place upstream of a midlatitude low pressure system in the early stage of development. Similar to the straight jet experiment an amplified ridge-trough pattern and a pronounced jet streak is found just downstream of ET (Fig. 13). Arguably, this provides a more favorable upper-level forcing for baroclinic development and the system just downstream of ET develops more strongly and rapidly than in the LC run (Fig. 14). The stronger development leads to the amplification of the leading edge of the upper-level wave train. The more pronounced upper-level wave, in turn, promotes stronger subsequent baroclinic development further downstream. The most pronounced impact of the ET system in this scenario is thus the promotion of downstream development leading to an amplified upper-level wave train (Fig. 14). Baroclinic feedback by stronger low-level systems – modified by diabatic processes – is found to be crucial for the coherent propagation of the amplified wave train.

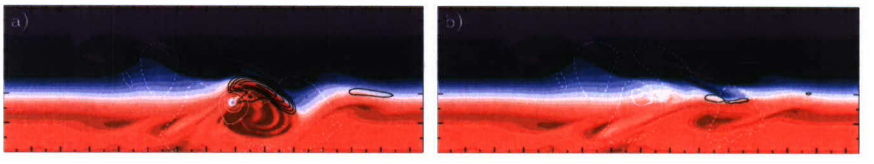


Figure 13: Same as Fig. 10 but for the developing case at 72 h. The ET run is shown in a) the LC run in b).

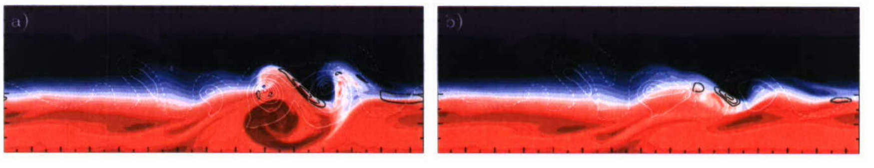


Figure 14: Same as Fig. 13 but at 108 h.

The advection patterns of the PV inversion diagnosis in the straight jet case suggest that a stronger storm should yield a larger amplification of the leading edge of the upper-level wave train. This idea is supported by sensitivity experiments with respect to the initial storm strength (not shown). However, we also find an increasing translation speed for stronger storms. Differences in translation speed lead to different relative locations of the tropical cyclone and the developing wave during ET. This highlights the complexity of the ET process but complicates the interpretation of our sensitivity experiments. In general, however, the sensitivity experiments show a stronger downstream impact for a more intense ET system.

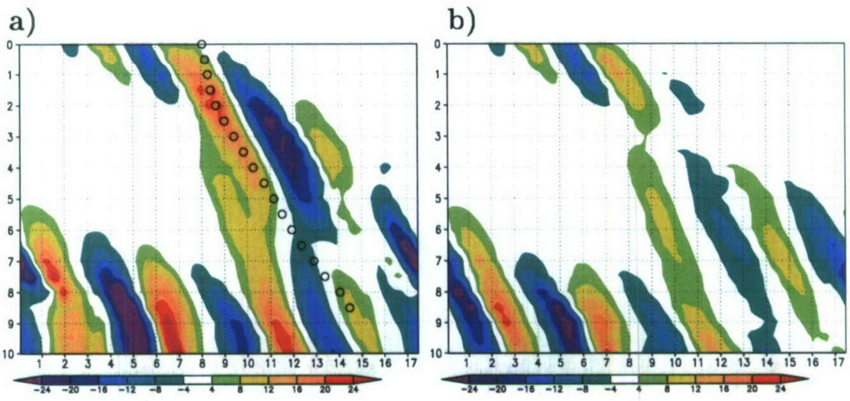


Figure 15: Same as Fig. 11 but for a) the ET run and b) the LC run of the developing case.

Mature case

A periodic initial perturbation is used in this scenario to excite baroclinic development. At the time of the interaction with the tropical cyclone the surface lows and the upper-level PV anomalies form vertically coherent and long-lived vortices in the midlatitudes (Fig. 16a). For the midlatitude system interacting with the ET system we observe a rapid disintegration of this coherent structure (Fig. 16b). This disintegration is arguably due to strong shearing of the upper-level PV anomaly and also due to a modification of the low-level frontal structure and diabatic reduction of the upper-level PV anomaly (not shown). In this scenario the decay of the coherent vortex yields a stronger zonal orientation of the upper-level flow in the vicinity of the ET system. Subsequently, the zonal flow orientation leads to the deformation of the downstream upper-level troughs also and thus the zonal flow orientation spreads into the downstream region (Fig. 16c and 17). The subsequent deformation of the upper-level troughs downstream - and thus the zonalization of the upper-level flow – can be regarded as the primary impact of ET on the downstream flow in this scenario. The impact, however, is significantly less than in the developing case.

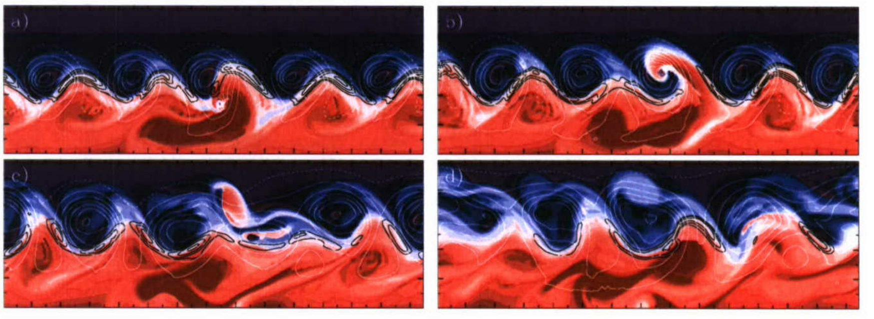


Figure 16: Same as Fig. 10 but for the ET run of the mature case at 108 h (a), 132 h (b), 180 h (c), and 240 h (d).

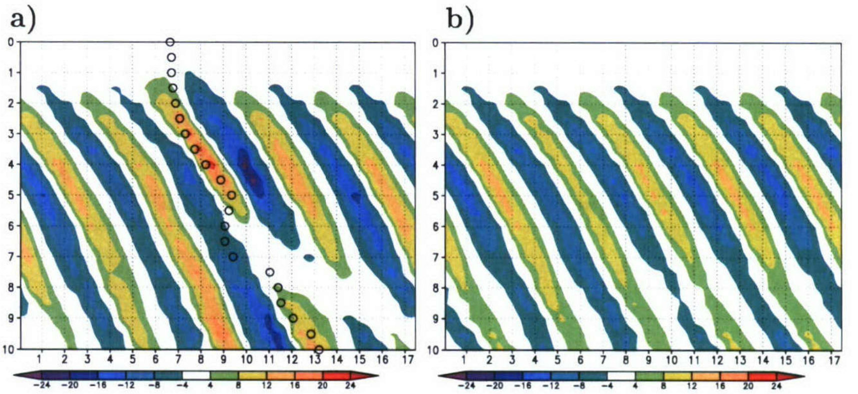


Figure 17: Same as Fig. 11 but for a) the ET run and b) the LC run of the mature case.

6 Low-level wind field during Extratropical Transition

Significant structural changes in the wind field occur during ET. Although the maximum wind speed typically decreases, the areal coverage of hazardous surface winds increases considerably and strong asymmetries develop. In order to provide accurate and timely warnings for an ET system these changes must be taken into account. Furthermore, reinsurance companies need information about the strength and spatial distribution of the surface wind field during ET for their risk assessment of the affected areas. A common assumption when constructing wind hazard maps for tropical cyclones is that the spatial structure of the wind field is determined by an axially-symmetric wind profile with a superposed wavenumber-one asymmetry representing the translation of the vortex. This results in a wind maximum and a broadening of the wind field to the right of the track. However, there are only limited observations available to detail the substantial changes in the wind field. In this study we use data from the idealised model scenarios described in the previous section to investigate the evolution of the surface winds during ET.

The surface wind field is analysed for an ET scenario in which the tropical cyclone moves ahead of a broad trough and a cold front into the warm sector of an occluding midlatitude low pressure system. At 72 h the tropical cyclone is well south of the midlatitude system with a translation speed of 5 m/s and has a symmetric wind field in the inner-core (Fig. 18a,b). At 132 h the tropical cyclone is located ahead of the cold front of the occluding midlatitude low (Fig. 18c). The translation speed of the tropical cyclone has increased to around 14 ms^{-1}. The surface wind field is now broader to the right of the direction of motion (Fig. 18d). No interaction with the cold front occurs as

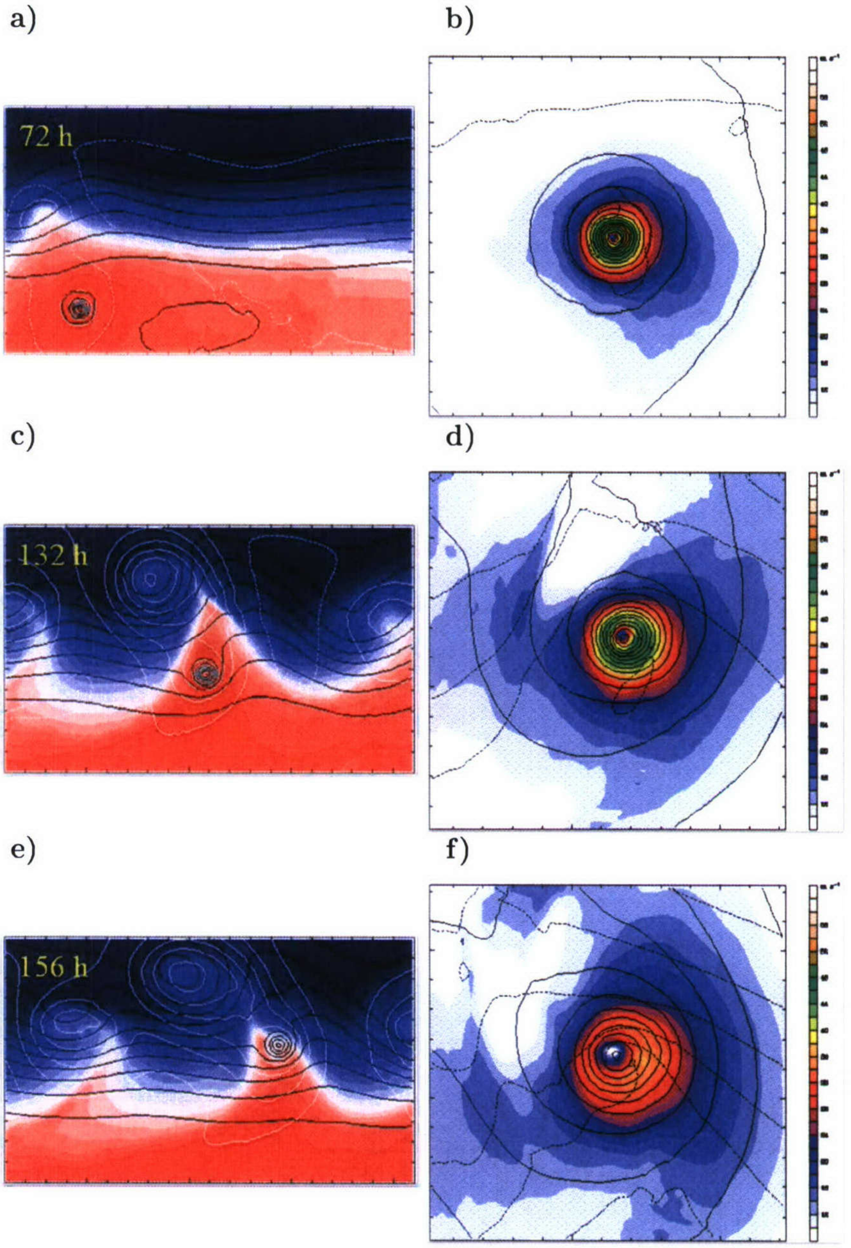


Figure 18: ET scenario from idealised modelling study. Left: potential temperature at 850 hPa (colour), surface pressure (white contours) and 500 hPa geopotential (black contours). Right: Surface pressure (solid contours), near surface potential temperature (dashed contours) and wind speed at approx. 30 m (colours). Fields shown after 72 h (a, b) 132 h (c, d) and 156 h (e, f) integration time.

the storm moves ENE. At 156 h the ET system is seen to interact with the warm front near the occlusion point (Fig. 18e). The maximum surface wind speed has decreased, although hurricane force winds are still seen to the east of the centre and the area covered by wind speeds in excess of 25 ms^{-1} has increased during ET.

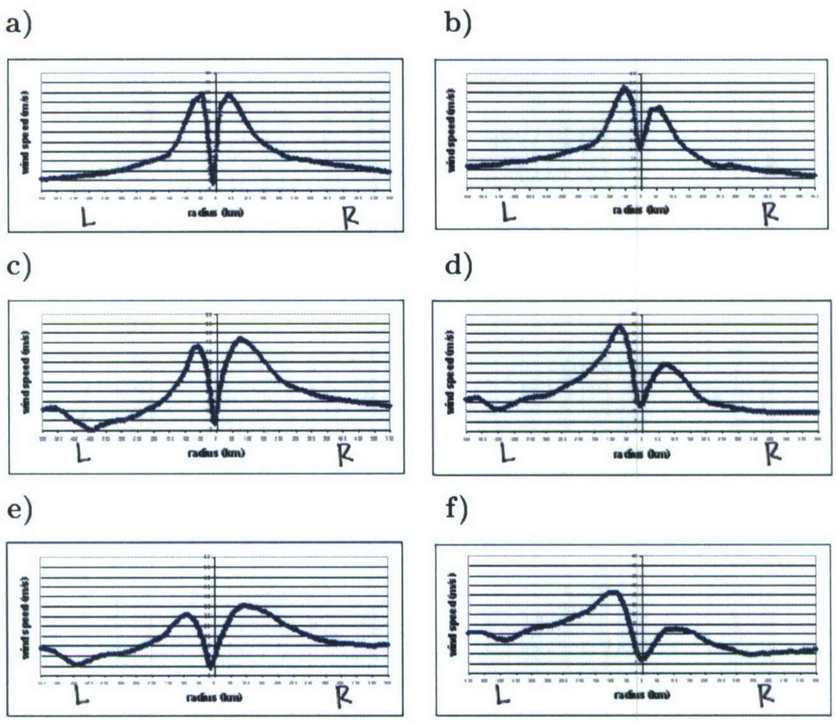


Figure 19: Radial profiles of near-surface wind speed perpendicular to direction of translation of tropical cyclone after 72 h (a, b) 132 h (c, d) and 156 h (e, f) integration time. Left: Total wind field. Right: wind field from which translation speed of tropical cyclone has been subtracted. Tick marks are every 50 km and horizontal lines every 5 ms^{-1}. L and R indicate side of profile to left and right of track respectively.

The changes in the surface wind field are analysed in more detail by constructing radial profiles of the wind field perpendicular to the direction of motion. Both the total wind field and the wind field from which the translation speed has been subtracted are displayed. At 72 h the profile is rather symmetric and the maximum wind speed is similar to the left and right of the track (Fig. 19a). When the translation speed is subtracted, the wind speed is higher to the left of the track (Fig. 19b). As the tropical cyclone enters the transformation stage of ET the wind field becomes broader to the right of the track where the maximum wind speed is higher also (Fig. 19c). However, the asymmetry cannot be explained by the translation speed alone, as the maximum wind speed without translation is much stronger to the left of the track (Fig. 19d). After 156 h the wind field weakens further and broadens. The asymmetry becomes more pronounced (Fig. 19e) but can still not be explained as a translating symmetric vortex (Fig. 19f).

This analysis shows that the simple model of a translating symmetric vortex does not explain the structure of the wind field in this case. The increased wind speed maximum on the right of the track is much lower than a simple addition of translation speed would suggest. Despite the differences in the maximum wind speed left and right of the track, the shape of the radial wind profiles become more symmetric when the translation speed is subtracted. This suggests that the broadening is associated with translation, but other dynamical mechanisms determine the maximum wind speed. Future studies are needed to quantify these mechanisms.

7 Collaboration with other groups

The analysis of the ensemble forecasts was carried out in close collaboration with Prof. Patrick Harr (Tropical Cyclone Formation/Structure/Motion Studies, award number N0001406WR20257). Doris Anwender visited the

Naval Postgraduate school in 2006 in order to facilitate this collaboration. Access to the ECMWF ensembles was possible through a special project entitled "The impact of tropical cyclones on extratropical predictability". The EPS experiments were carried out in collaboration with Dr. Martin Leutbecher of ECMWF. The potential vorticity inversion was conducted in collaboration with Dr. Christopher Davis of NCAR. The interpretation of the idealised modelling was enhanced through discussions with Prof. Daniel Keyser of SUNY at Albany. The data for the analysis of the impact of dropsonde data on downstream forecasts was provided by Dr. Sim Aberson of NOAA/AOML/HRD.

8 Outside support

Support towards the project has been provided by the University of Karlsruhe / Forschungszentrum Karlsruhe in the form of salaries for the Principal Investigator and for Mr. Michael Riemer. Computing support for most of the program development work was provided by the Institut für Meteorologie und Klimaforschung and by the University of Karlsruhe Computing Centre.

9 Graduate students

University higher degrees emanating from this project: 2 Ph.D. (1 Female, 1 Male), 1 M. Sc. (Diplom, 1 Female).

10 Honours/Awards/Prizes

2006

Mr. Michael Riemer received the Max Eaton Prize at the 27th AMS Conference on Hurricanes and Tropical Meteorology held in Monterey, California in April 2006.

2007

Ms. Doris Anwender received a German Research Foundation travel award to visit the 7th EMS Annual Meeting / 8th European Conference on Applications of Meteorology held in San Lorenzo de El Escorial, Spain.

11 Publications arising from this project

11.1 Refereed journal papers

Anwender, D., P. A. Harr, and S. C. Jones, 2008: Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones: Case studies. *Mon. Wea. Rev.* (in press).

Davis, C. A., S. C. Jones, and M. Riemer, 2008: Hurricane vortex dynamics during Atlantic extratropical transition. *J. Atmos. Sci.* (in press).

Harr, P. A., D. Anwender, and S. C. Jones, 2008: Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones: Methodology and a case study of Typhoon Nabi (2005). *Mon. Wea. Rev.* (in press).

Jones, S. C., D. Anwender, and M. Riemer, 2006: Die Umwandlung tropischer Wirbelstürme in außertropische Tiefdruckgebiete und ihr Einfluss auf das Wetter der mittleren Breiten. *promet 32*.

Riemer, M., S. C. Jones, and C. A. Davis, 2008: The impact of extratropical transition on the downstream flow: an idealised modelling study with a straight jet. *Q. J. R. Meteorol. Soc. 134*, 69-91.

11.2 Journal papers in preparation

Anwender, D., S. Jones, M. Leutbecher, and P. A. Harr 2008: Sensitivity experiments for ensemble forecasts of the extratropical transition of Typhoon Tokage (2004).

Riemer, M., and S. Jones, 2008: Interaction of tropical cyclones with midlatitude baroclinic waves in idealised scenarios of extra-tropical transition.

11.3 Conference papers

2006

The following papers were presented at the 27th AMS Conference on Hurricanes and Tropical Meteorology held in Monterey, California in April 2006:

Anwender, D., M. Leutbecher, S. C. Jones, and P. A. Harr (2006). Sensitivity of ensemble forecasts of extratropical transition to initial perturbations targeted on the tropical cyclone.

Harr, P. A., D. Anwender, and S. C. Jones (2006). Predictability associated

with the downstream impacts of the extratropical transition (ET) of tropical cyclones.
Riemer, M.: The impact of extratropical transition on the downstream flow: idealised modeling study.
Riemer, M., Hofheinz, P., and Jones, S.C.: Structural changes of low level wind field of tropical cyclones in idealised extratropical transition scenarios.

The following papers were presented at the Second THORPEX International Science Symposium (STISS) held in Landshut, Germany:

Anwender, D., M. Leutbecher, S. C. Jones, and P. A. Harr (2006). Sensitivity of ensemble forecasts of extratropical transition to initial perturbations targeted on the tropical cyclone.
Boettcher, M., S. C. Jones and S. Aberson: The impact of dropsonde observations around tropical cyclones on the medium-range forecast for Europe.
Davis C., S. C. Jones, and M. Riemer (2006). WRF simulation and diagnosis of the extratropical transitions of Irene (2005).
Harr, P. A., Doris Anwender, and Sarah Jones (2006). Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones.
Harr, P. A., and Jones: The impact of extratropical transition on the downstream midlatitude predictability.
Riemer, M., S. C. Jones, and C. Davis: The impact of extratropical transition on the downstream flow: Idealised modelling study.

2007

The following papers were presented at the joint meeting of the German, Austrian and Swiss Meteorological Societies (DACH-2007) held in Hamburg, Germany:

Anwender, D., M. Leutbecher, S. C. Jones, and P. A. Harr (2007). Außertropische Umwandlung von tropischen Wirbelstürmen im ECMWF Ensemblevorhersagesystem: Fallstudien und Sensitivitätsexperimente.
Riemer, M., S. C. Jones, and C. A. Davis (2007). Außertropische Umwandlung tropischer Wirbelstürme: Einfluss auf das Strömungsmuster in den mittleren Breiten.

The following paper was presented at the 7th EMS Annual Meeting / 8th European Conference on Applications of Meteorology held in San Lorenzo de El Escorial, Spain:

Anwender, D., M. Leutbecher, S. C. Jones, and P. A. Harr (2007). Extratropical transition in ECMWF ensemble forecasts: case studies and sensitivity experiments.

2008

The following papers will be presented at the 28th AMS Conference on Hurricanes and Tropical Meteorology held in Orlando, Florida:

Anwender, D.: Sensitivity experiments for ensemble forecasts of extratropical transition.

Riemer, M., and S. C. Jones: Interaction of tropical cyclones with midlatitude baroclinic waves in idealised scenarios of extra-tropical transition.

11.4 Theses

2006 M. Sc. (Diplom)

Boettcher, M.: Einfluss von Dropsondendaten aus tropischen Wirbelstürmen auf die Wettervorhersage für Europa (Impact of dropsonde data taken in tropical cyclones on the weather forecast for Europe).

2007 Ph.D.

Anwender, D.: Extratropical transition in the Ensemble Prediction System of the ECMWF: case studies and experiments.

Riemer, M.: The impact of extratropical transition on the downstream flow: an idealised modelling study.

References

Aberson, S. D. (2003). Targeted observations to improve operational tropical cyclone track forecast guidance. *Mon. Wea. Rev. 131*, 1613–1628.

Boettcher, M. (2006). Einfluss von Dropsondendaten aus tropischen Wirbelstürmen auf die Wettervorhersage für Europa. http://www.imk.uni-karlsruhe.de/3131.php .

Harr, P. A., D. Anwender and S. C. Jones (2007). Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones: Methodology and a case study of Typhoon Nabi (2005). *Mon. Wea. Rev.* , in press.

Jones, S. C., P. A. Harr, J. Abraham, L. F. Bosart, P. J. Bowyer, J. L. Evans, D. E. Hanley, B. N. Hanstrum, R. E. Hart, F. Lalaurette, M. R. Sinclair, R. K. Smith and C. Thorncroft (2003). The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Weather and Forecasting 18*, 16–56.

Puri, K., J. Barkmeijer and T. N. Palmer (2001). Ensemble prediction of tropical cyclones using targeted diabatic singular vectors. *Q. J. R. Meteorol. Soc. 127*, 709–731.

Szunyogh, I., Z. Toth, R. E. Morss, S. J. Majumdar, B. J. Etherton and C. H. Bishop (2000). The effect of targeted observations during the 1999 winter storm reconnaissance program. *Mon. Wea. Rev. 128*, 3520–3537.

Szunyogh, I., Z. Toth, A. V. Zimin, S. J. Majumdar and A. Persson (2002). Propagation of the effect of targeted observations: The 2000 winter storm reconnaissance program. *Mon. Wea. Rev. 130*, 1144–1165.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
28-03-2008

2. REPORT TYPE
Final Technical Report

3. DATES COVERED *(From - To)*
01-01-2006 to 28-03-2007

4. TITLE AND SUBTITLE
The Predictability of Extratropical Transition and of its Impact on the Downstream Flow

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-06-1-0432

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Sarah C. Jones, Doris Anwender, Michael Riemer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institut für Meteorologie und Klimaforschung
Universität Karlsruhe
Kaiserstr. 12, 76128 Karlsruhe
GERMANY

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In this project we investigated the basic mechanisms that determine the predictability of tropical cyclones undergoing extratropical transition (ET) and of their impact on the downstream flow. The analysis of ensemble forecasts for five ET cases showed that uncertainty is associated with the location and amplitude of a characteristic upper-level trough-ridge-trough pattern consisting of the trough that interacts with the tropical cyclone, a ridge directly downstream and a second trough downstream of the ridge. Experiments for Typhoon Tokage (2004) with the ensemble prediction system of the European Centre for Medium Range Weather Forecasts showed that targeted perturbations led to increased spread around and shortly after ET time whereas the spread due to stochastic physics increased at a later time as the influence of the targeted perturbations decreased. Idealized modelling combined with potential vorticity inversion was used to quantify the mechanisms responsible for this variability. Furthermore, dropsonde data in the vicinity of tropical cyclones were shown to reduce the medium-range forecast error for the downstream flow.

15. SUBJECT TERMS
Extratropical transition, tropical cyclones, predictability, ensemble forecasts, idealized modelling, potential vorticity

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	SAR	39	Prof. Sarah C. Jones
					19b. TELEPHONE NUMBER *(Include area code)* +49-721-608-6751